

The measurement of concrete permeability

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This paper describes the construction and operation of an apparatus for the measurement of concrete permeability. The concrete samples used in the apparatus are cast in epoxy resin before insertion in a pressure cell. Uniaxial water flow, under pressures up to 3.5 MPa, is ensured by O-ring seals.

Results are presented for the permeability of laboratory samples with water/cement ratios varying from 0.35 to 0.75.

Key words: concrete, permeability, apparatus.

Ce rapport décrit les procédures de construction et d'opération d'un appareil servant à mesurer la perméabilité du béton. Les échantillons de béton sont moulés dans une résine époxy avant leur insertion dans une cellule de pression. L'utilisation de joints annulaires d'étanchéité permet d'assurer un écoulement d'eau uniaxial, sous des pressions pouvant s'élever jusqu'à 3.5 MPa.

Les résultats obtenus pour la perméabilité d'échantillons de laboratoire ayant des rapports eau-ciment variant entre 0.35 et 0.75 sont présentés.

Mots clés: béton, perméabilité, appareillage.

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Introduction

In 1979 the ISO/TC/71, Subcommittee on Test Methods, proposed a method for measuring concrete permeability for adoption by member countries (ISO 1983). Since there was very limited data available on the feasibility of the method it was decided to carry out an investigation of permeability measurement to develop this information.

The initial apparatus, designed on the principle outlined in the ISO proposal, was soon abandoned because unacceptable leakage had occurred and one-dimensional flow of water could not be ensured.

The measurement of concrete permeability has been obtained by several methods that measure the rate of water flow through concrete samples under a constant hydraulic gradient, the most popular being the one adopted by the Corps of Engineers (1973) as standard (CRD-C48-73). This standard uses a paraffin/resin mixture to coat the specimen sides followed by a layer of 200 to 300 penetration asphalt between the specimen and wall of the pressure vessel. Paraffin/resin layers at each end of the specimen enclose the asphalt layer.

Concrete generally has a low permeability. Consequently, either the length of path along which permeability is to be measured must be relatively small or the driving force must be relatively large to avoid an undue length of time required for the test. The Corps of Engineers method can only be used at low pressures,

otherwise the seal between the specimen and vessel wall breaks down and leakage occurs around the edges of the specimen. Such leakage gives totally erroneous results.

A method previously described (Gjorv and Loland 1978) solves the edge-sealing problem by using epoxy to cement the concrete specimen inside a discardable plastic cylinder and using properly designed O-ring seals between the pressure vessel wall and the plastic cylinder. Much higher pressures can be used to drive the water through the specimen with this method. This means that larger, more representative specimens can be used and test results obtained in a reasonable length of time. The apparatus described below was based on a modification of that developed by Gjorv and Loland.

Test apparatus

The test equipment consisted of a series of pressure cells connected to a hydraulic line capable of subjecting the cells to 3.5 MPa (500 psi) pressure. Each cell contained a cylindrical concrete sample, through which water passed in the longitudinal direction. Design of the equipment and preparation of the sample ensured one-dimensional flow. The volume of water passing through the concrete sample, per minute, was measured and recorded.

Pressure cells

A pressure cell was designed in which a concrete

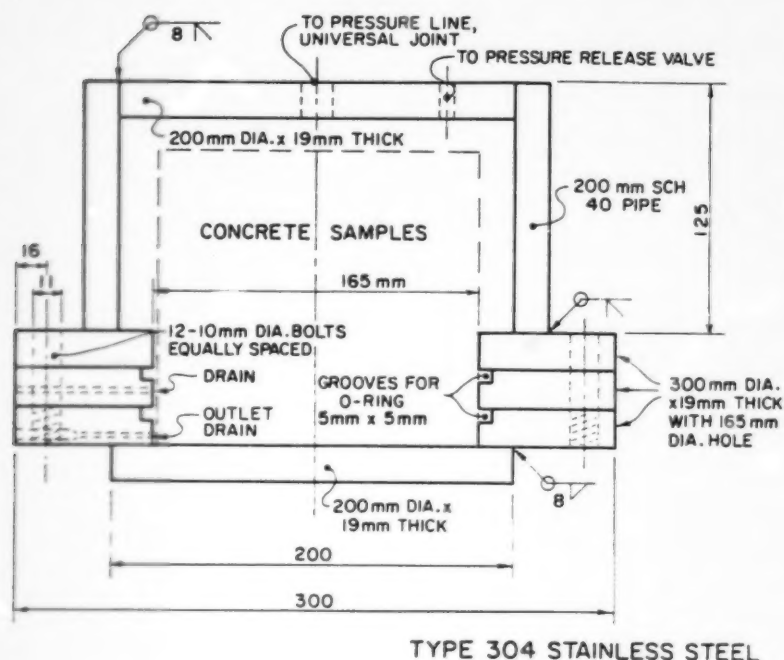


FIG. 1. Details of pressure cell.

sample could be subjected to a constant, externally maintained hydraulic pressure. Details of the cell construction are shown in Fig. 1.

The cell consisted of three parts: (i) A 200 mm diameter base supported the cylindrical concrete sample. A 300 mm circular hollow collar welded to this plate fitted closely around the sample. A groove was cut in the collar, adjacent to the sample wall, in which an O-ring was fitted. This provided a watertight seal between container and sample. (ii) A second hollow collar was placed over the first, also grooved on its upper inside surface and fitted with an O-ring. Thus a second seal was provided. (iii) A cylinder, closed at one end and welded to a third collar at the other end, fitted over the top and sides of the concrete sample. Bolts secured the three collars tightly together.

A fitting on the top of the cell permitted it to be connected to a high pressure hydraulic system, and a valve allowed the release of pressure to the atmosphere.

Thus water entered the top of the cell under high pressure, passed through the concrete sample, and escaped from the cell by means of an outlet in the base. This outlet was connected to a measuring system, discussed later.

To ensure that water flow through the sample was one dimensional, the sides of the concrete sample were sealed with a fibre glass resin compound. This procedure is described in detail below. Water flowing



FIG. 2. Pressure cell components.

along the sides of the sample was prevented from flowing through the cell, by the O-rings. Any water managing to pass by the top O-ring would drain out of the cell by means of an outlet in the centre collar. These safeguards ensured that only water flowing directly through the top and bottom of the sample was measured at the

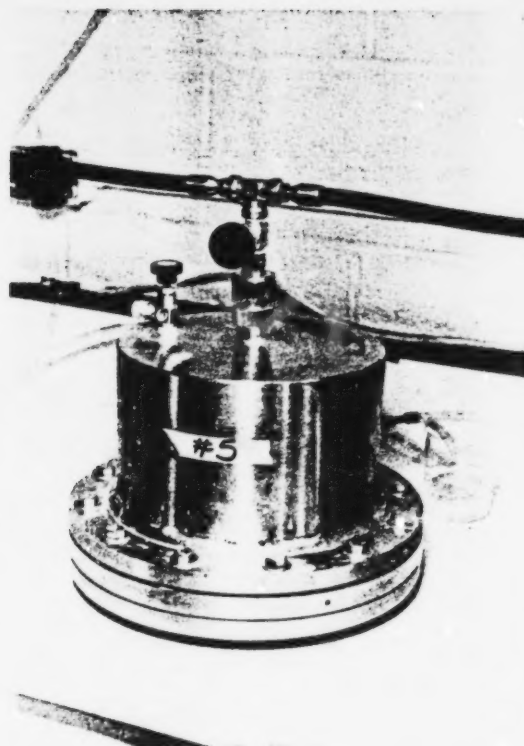


FIG. 3. Assembled pressure cell.

outlet.

The prototype cell was constructed of aluminum. It was found that alkalis in the concrete cement reacted with the interior cell surface, causing corrosion. Stainless steel was found to be more resistant and subsequent cells were constructed of this material.

The major components of a pressure cell are shown in Fig. 2 together with a resin-jacketed concrete sample in the upper left portion of the figure. A total of five cells was constructed.

An assembled pressure vessel is shown connected to hydraulic lines in Fig. 3. The drain hole in the centre ring is clearly visible.

At the time of preparation of this paper (May 1983) a set of five stainless steel cells could be manufactured for \$5750.¹

Hydraulic system

All five cells were connected in parallel, by a high pressure line, to a pressure vessel as shown in Fig. 4.

This vessel consisted of two closed hollow cylinders

fitted with collars, which were bolted together. A rubber diaphragm was clamped between the collars, dividing the interior of the vessel into upper and lower halves.

The top section was connected directly to a nitrogen tank, with the bottom section connected, via water-filled lines, to the pressure cells. When the gas pressure in the top of the vessel was increased (by means of a valve on the nitrogen tank), the diaphragm was pushed downwards, pressurizing the water in the lower half of the vessel. This increased the water pressure in the lines, and in turn, the pressure in each cell.

The rubber diaphragm was necessary to prevent the dissolution of nitrogen by the water under the high pressure used. The pressure in the water drops as it passes through the concrete specimen and dissolved gases come out of solution and form bubbles in the water. It has previously been found that these bubbles cause variations in the measured permeability of the concrete (Gjørsv and Løland 1978).

Pressure gauges were placed on both the top and bottom lines to the vessel. It was necessary to ensure that the pressure remained approximately equal on opposite sides of the diaphragm, to avoid breakage of the thin rubber membrane.

A water pressure lower than the indicated gas pressure meant that the reservoir in the base of the pressure vessel was no longer filled. Thus the required pressure could not be maintained in the lines without adding water to the system. Initially this addition was accomplished by pumping water from a hydraulic jack into the base of the pressure vessel. Alternatively, valves on top of each pressure cell could be temporarily closed and a vacuum created in the main water line. Water at atmospheric pressure was then allowed to flow into the line from an outside source. This appeared to be effective, and no 'pockets' of trapped air were observed.

It should be noted that each cell could be individually disconnected from the main hydraulic line, with no effects on the remaining cells.

Measurement of water flow

A section of flexible plastic pipe connected the flow from each cell outlet to a 5 m long capillary tube.

The relative ease with which water passed through the concrete sample was indicated by the speed with which the water moved up the tube.

The distance the water moved up the tube in a given time period was measured. The tubes had been individually calibrated so that the volume of water passing through the concrete per time unit could be calculated.

Concrete test samples

Design and preparation of mixes

Samples 150 mm high and 150 mm in diameter were

¹Private communication, Wejay Machine Products Co. Ltd., 600 O'Connor Drive, Kingston, Ontario.

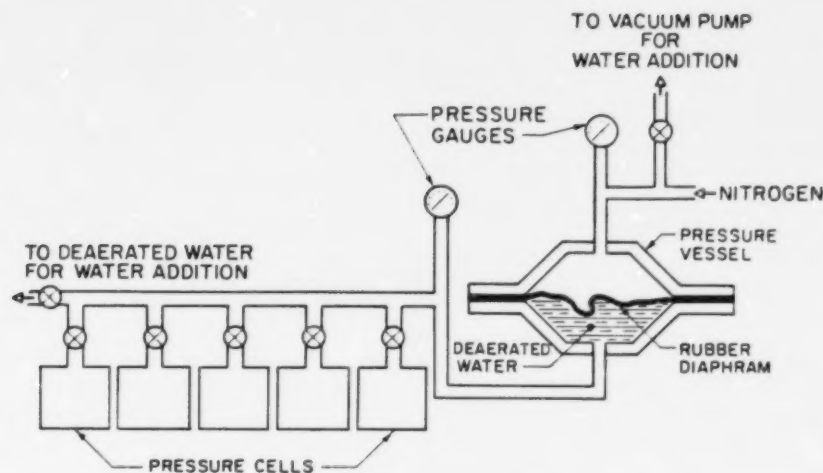


FIG. 4. Connection of cells to pressure vessel.

TABLE 1. Concrete/permeabilities

Mix No.	Water/cement ratio	Air content (%)	f'_c (MPa)	k (m/s)	V (%)
1	0.35	4.0	33.1	0.37×10^{-13}	69.9
2	0.40	5.0	32.5	2.00×10^{-13}	
3	0.45	5.8	26.1	1.26×10^{-13}	
4*	0.50	2.0	28.4	7.1×10^{-13}	32.8
5	0.55	7.3	20.0	4.68×10^{-13}	
6	0.60	6.2	26.4	7.50×10^{-13}	
7	0.65	6.8	16.6	8.14×10^{-13}	36.8
8	0.70	8.0	12.3	9.13×10^{-13}	
9	0.75	6.5	10.6	10.9×10^{-13}	

*Initial mix, non air entrained.

required for testing in the pressure cells. At least 10 of these were produced for each different mix design tested. As well, four 300 mm high by 150 mm diameter samples were made for compression strength tests on each mix.

The initial mix tested was a control mix with a water/cement ratio of 0.5, 50–75 mm slump, and an air content of 2%. A series of nine mixes was subsequently prepared in a similar fashion, with a range of water/cement ratios and air contents as shown in Table 1.

The mixes were designed in accordance with the ACI manual of Concrete Practice (Standard 211-1-77). CSA type 10 portland cement was used. The coarse aggregate was laboratory stock, 12 mm maximum size crushed limestone. Fine aggregate was natural siliceous sand, and the moisture content of the sand was checked before preparation of each mix.

Mixes were prepared according to CSA Standard A23.1 and A23.2. Slump tests were performed on the

plastic concrete and mix components adjusted until the desired 50–75 mm slump was achieved. Air content of the concrete mix was determined by the pressure method (ASTM C231-78). A predetermined amount of air-entraining agent was added to the mixing water for the batches requiring entrained air.

Moulds for the samples were made of sections of PVC pipe, closed at one end. A small hole in the base of the mould allowed an air hose to be applied to aid in removal of concrete from the mould. Moulds were lightly oiled before addition of the concrete in three layers, with mechanical vibration after the placing of each layer. The samples were then covered with plastic sheeting for 24 h, at which time the concrete cylinders were removed from the moulds and placed in a curing room (20°C, 100% relative humidity). After 28 days the four (150 mm × 300 mm) compressive strength cylinders were removed, capped with a sulphur compound, and subjected to a compressive strength test. The results of these tests are shown in Table 1.

Preparation of samples for permeability testing

Samples were removed from the curing room at least 24 h before jacketing, and allowed to air dry. A dry concrete surface was necessary to achieve a good bond with the fibre glass resin.

The concrete cylinder was then placed on its end on a hollow circular Plexiglas base in which a groove had been cut. Into this groove the base of a split section of Plexiglas pipe was set, encircling the concrete sample. The Plexiglas cylinder had an inside diameter 12 mm larger than the outside diameter of the concrete sample. Both the sample and Plexiglas were of equal height.

Before assembly, the inside of the Plexiglas cylinder was coated with mould-release wax. The joint at the

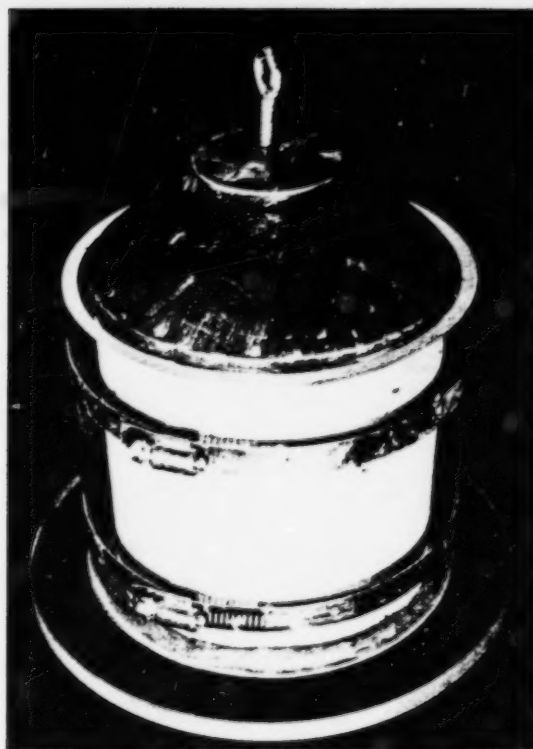


FIG. 5. Sample ready to be jacketed.

base of the cylinder and sample was sealed with a 6 mm strip of modelling clay. A compound consisting of equal parts by weight of fibre glass resin and silica flour was used to jacket the specimen. The silica flour was used to reduce the heat generated and the shrinkage of the resin on hardening.

The fibre glass compound was poured into the space between the cylinder and sample, creating a 6 mm thick jacket extending to the ends of the sample. A cover was used over the end of the specimen to prevent resin from being spilled on the top surface of the concrete. A sample in the Plexiglas mould prior to pouring the resin is shown in Fig. 5.

After hardening of the resin, the Plexiglas moulds were removed for reuse. Samples were placed in water for at least 24 h to ensure some degree of saturation before assembly in the pressure cells. Vacuum saturation is very advantageous if the equipment is available. This fully saturates the concrete prior to it being placed in the cells and steady state water flow is established in 1 or 2 days. Steady state flow is easily verified by comparing rate of flow readings on successive days. There is a large variation in flow rate initially but this reduces markedly once steady state flow has been

established. Without vacuum saturation some relatively impermeable concretes require up to 2 weeks under pressure before steady state flow is obtained.

In subsequent use of the apparatus it was found that all difficulties of occasional jacket cracking and bond failure experienced using fibre glass resin were eliminated if epoxy resin was used for the jacketing material. This resin does not shrink significantly on hardening and the use of silica flour as a filler is not necessary. While epoxy resins are more expensive than fibre glass the epoxy is recommended over the fibre glass resin for practical considerations.

Cell assembly and operation

The concrete sample was placed on the cell base, fitted with an O-ring, the second steel collar, and a second O-ring. The main body of the cell was placed on top, and the three steel flanges bolted securely together.

The cell was filled with deaerated (boiled) water by means of the top outlet. It was then connected, by means of this same fitting, to the water lines, which had been previously filled. The valves on the individual water lines to the cells were opened and the pressure in the system increased to 3.5 MPa.

Readings of flow through the cells were recorded, until a steady state of flow was reached. Flow was then recorded over a period of several days.

Analysis and test results

To compare the relative resistance to water flow through these samples, coefficients of permeability were calculated.

For one-dimensional water flow through a saturated medium, Darcy's law states that

$$q = A \cdot k \cdot i$$

where q = volume of water flowing per unit time (m^3/s), A = cross-sectional area of sample (m^2), k = coefficient of permeability (m/s), and i = hydraulic gradient across sample (m head/m).

The sample area was computed from known dimensions. The pressure at the cell outlet at the base of the concrete sample is atmospheric pressure, 101 kPa, which can be expressed as an equivalent water column of 10.3 m. Pressure on the top of the concrete was 3.5 MPa, which can be expressed as 357 m of water.

The hydraulic gradient in the cell was equal to the head loss across the cell divided by the length of the cell across which water flows. All specimens were 150 mm in diameter and 150 mm long, giving:

$$i = \frac{357 \text{ m} - 10.3 \text{ m}}{0.150 \text{ m}} = 2310 \text{ m head/m}$$

and

$$k = \frac{q \text{ (m}^3\text{/s)}}{0.0177 \text{ (m}^2\text{)} \times 2310 \text{ (m/m)}} = \frac{q}{40.9}$$

Values of k corresponding to the average flow rates measured are given in Table 1. Where four or more identical specimens were tested the coefficient of variation, v , has been calculated.

From the above results, it can be seen that in general the permeability, k , increases as the strength of the concrete decreases. The strength of 20 MPa reported for mix 5 was obtained from the four cylinders of mix 5 used for compressive strength determination. This is lower than would be expected for a water/cement ratio of 0.55 and, even though there is no evidence that the strength result is indeed erroneous, the strength reported should be treated as suspect.

It should be noted once again that all mixes were prepared from similar materials, were subject to the same mixing procedure, and underwent similar curing periods prior to testing. All samples were saturated by simple immersion prior to being placed in the test cells. Test data was recorded only after a steady state flow was reached. In these ways, an attempt was made to standardize the effects of the various procedures on the k values obtained for the concrete samples. It would be expected that the observed variation of the coefficient of permeability was due, for the most part, to normal variations in concrete matrix and air contents. Concrete permeability is caused mainly by a relatively few interconnected capillary channels. Consequently, individual specimens show fairly large deviations from the mean caused by a few more or a few less capillary channels.

Conclusions

This test method and apparatus appears to present a valid means of determining coefficient of permeability for concrete mixes with a wide range of water/cement

ratios and air contents. The simultaneous use of five cells allows an estimate to be made of the effects of inhomogeneities in the concrete, or aggregate, used. As well, a number of different mixes can be tested under similar conditions. The test is adaptable in that the hydraulic gradient applied to the sample can be varied, as well as the fluid used for testing. (That is, the effect of a fluid other than water, or the addition of chemicals to the water used, could be examined.) In this way, the test can be modified to simulate the actual field conditions to which a concrete will be subjected.

Recommendation

It is recommended that Canadian Standards Association (CSA) Committee A23.2, Methods of Test for Concrete, give serious consideration to the adoption of the above apparatus and test method as a Canadian standard test method.

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- CORPS OF ENGINEERS. 1973. Method of test for water permeability of concrete. CRD-C-48-73. In Handbook for concrete and cement. Corps of Engineers, Vicksburg, MS.
- GIØRV, O. E., and LØLAND, K. E. 1978. Effects of air on the hydraulic conductivity of concrete. FCB Report. Cement and Concrete Research Institute, Norwegian Institute of Technology—SINTEF, Trondheim, Norway.
- ISO. 1983. Concrete: Determination of permeability. ISO DIS 7032 (draft).